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NASA TECHNICAL
MEMORANDUM

NASA TM X-53094

JULY 23, 1964

FACILITY FORM 602

N64-33185 (ACCESSION NUMBER)	(THRU)
32 (PAGES)	1 (CODE)
NASA tmX 53094 (NASA CR OR TMX OR AD NUMBER)	11 (CATEGORY)

NASA TM X-53094

INTERCELLULAR MOBILITY OF FLUIDS WITHIN HONEYCOMB-REINFORCED COMMON BULKHEADS (BULKHEAD PURGING)

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XEROX	\$ 2.00
MICROFILM	\$ .50

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ABSTRACT

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The flow of gases through annular and rectangular face-sealed honeycomb specimens was studied as a function of pressure drop to develop purging and evacuation procedures for the S-IV vehicle. Extrapolation of steady state results for laboratory specimens to unsteady state conditions for full scale vehicles was accomplished by using an energy/mass transport analogy.

The results indicated that mass transport through the honeycomb is fast enough to cause concern but too slow to permit rapid purging or evacuation. Although purging and evacuation times could be greatly decreased by use of perforated honeycomb core material, this would offset any advantages resulting from confining or isolating individual leaks. Further study of these factors is needed.

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RESEARCH AND DEVELOPMENT OPERATIONS

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INTERCELLULAR MOBILITY OF FLUIDS WITHIN HONEYCOMB-REINFORCED COMMON BULKHEADS (BULKHEAD PURGING)

SUMMARY

The flow of gases through annular and rectangular face-sealed honeycomb specimens was studied as a function of pressure drop to develop purging and evacuation procedures for the S-IV vehicle. Extrapolation of steady state results for laboratory specimens to unsteady state conditions for full scale vehicles was accomplished by using an energy/mass transport analogy.

The results indicated that mass transport through the honeycomb is fast enough to cause concern but too slow to permit rapid purging or evacuation. Although purging and evacuation times could be greatly decreased by use of perforated honeycomb core material, this would offset any advantages resulting from confining or isolating individual leaks. Further study of these factors is needed.

INTRODUCTION

The S-IV stage of the Saturn I launch vehicle and the S-II and S-IVB stages of the Saturn V launch vehicle use hydrogen and oxygen as the fuel and oxidizer. For each stage, the hydrogen container is located immediately above the oxygen container. The containers are separated by honeycomb reinforced common bulkheads which consist of aluminum face sheets adhesively bonded to fiberglass honeycomb material. The large sizes and hemispherical shapes of these bulkheads together with the extremely low temperature environments suggest the possibility of leakage of either hydrogen or oxygen or both into the honeycomb cores. Because of the extreme flammability of hydrogen/air and hydrogen/oxygen mixtures and also the sensitivity of the honeycomb material and adhesive to impact while in contact with liquid oxygen, it was considered desirable to evacuate and/or purge the bulkheads before propellant loading.

Although conventional fluid flow phenomena are not well understood, much less is known about the flow of fluids through composite and cellular materials and structures. Therefore, this investigation was carried out to obtain data needed for developing evacuation and purging procedures for the Saturn hydrogen/oxygen stages and to contribute to basic knowledge of transport phenomena within composite and/or cellular materials.

ACKNOWLEDGMENT

All samples used for this study were prepared by the Non-Metallic Materials Branch of this Division.

EXPERIMENTAL

Two basic sample configurations were employed: rectangular (FIG 1) for basic data and ease of testing, and annular (FIG 2) for elimination of possible end effects (such as leakage) and for studies on a geometry specific to the bulkhead configuration.

The honeycomb core of the one-inch thick "sandwich" was 3/16-inch cell, 4 pounds per cubic foot, 91LD phenolic fiberglas material which is consistent with the bulkhead used for the S-IV stage. The adhesive was HT-424, an epoxy-phenolic, supplied by Bloomingdale Rubber Company, having an uncured thickness of 0.015 inch. All face sheets were of 2014-T6 aluminum. Before bonding, the aluminum was cleaned in a dilute sodium dichromate-sulfuric acid solution at 150°C (302°F) to 160°C (320°F) for 20 minutes. The cleaning solution was rinsed off with distilled water, and the metal was allowed to air dry. The sandwich was bonded at 171°C (340°F) for 40 minutes between heated plates under a pressure of 25 psi. This procedure completed the annular specimens. However, for the rectangular specimens, the sides parallel with the flow direction were completely sealed by potting with Armstrong C-1 epoxy (SiO_2-filled). This material also was used to bond the end plates. Flow was normal to the ribbon direction for all rectangular specimens except for one set (designated 6 x 6*) for which the flow was parallel to the ribbon direction. Approximately 1/8-inch space was left between the end plates and the fore and aft edges of the honeycomb to allow free gas distribution both upstream and downstream of the honeycomb sandwich (FIG 1). In this way, the <u>rectangular</u> specimens were completely self-contained, whereas a fixture was required to contain the gas entering or leaving the periphery of the <u>annular</u> specimens. For both pressure and vacuum runs, flow rates for the annular specimens were measured at the center port to eliminate effects of possible fixture leakage. Thus, the direction of flow was toward the periphery for vacuum runs and away from the periphery for pressure runs on these specimens.

Sketches of all flow arrangements, both for pressure and vacuum and for annular and rectangular specimens, are shown in FIG 3, where the flow is from left to right in all cases. Equilibrium flow normally occurred in a few seconds, but about five minutes were allowed before flow measurements were made, and steady state was verified by repeated readings for a brief period.

FIG 3a shows a rectangular specimen under vacuum permeation testing. Upstream pressure was essentially barometric, and downstream pressures generally varied from 5 to 25 Torr, depending on the permeation rate. The flowmeter shown was calibrated periodically against and sometimes supplemented by a wet test meter. Further calibration was provided by the Test Laboratory at this Center.

The test setup for the annular specimens (FIG 3b) was similar to that for the rectangular specimens except that the above-mentioned fixture was required because of the open peripheral honeycomb face.

Pressure tests (with various gases) as shown in FIG 3c and 3d were conducted at pressure drops of 5, 15, 25, 35, and 50 psi (all ± 0.25 psi). A 12-inch precalibrated bourdon tube pressure gauge was used for monitoring upstream pressure. Downstream pressure was essentially atmospheric, the flowmeters imposing a pressure drop of less than 0.5 inch of water.

Runs were made in a somewhat random order and by several operators to reduce systematic experimental errors.

Data obtained for the rectangular specimens for air are shown in Table I. Tables II, III, and IV show similar data for annular specimens for air, nitrogen, and helium, respectively.

RESULTS

Rectangular Specimen

FIG 4 presents average air flow rates for rectangular specimens as functions of ΔP. Also included are the same flow rates as functions of $\Delta(P^2)$. The portions of the curves indicating flow rates for relatively low pressure drops are markedly non-linear. This suggests that some bending and distortion of the specimens take place because of the pressure drop imposed during testing. This distortion appears to increase with increasing pressure drop to approximately 15 psi.

Inspection of the flow rates for pressure drops of 15 psi and greater indicates that the ΔP plots generally depart from a visually fitted straight line in a more or less random fashion, whereas the departures for the $\Delta(P^2)$ plots are more systematic, with the first and last points generally falling below the line and the intermediate points above. This more nearly linear behavior noted for the ΔP plots suggests that a major component of the total flow is molecular in nature. On the other hand, the filled symbols (representing the data for the vacuum runs) are more consistent with the data for the pressure runs for the $\Delta(P^2)$ plots. This suggests that the flow is viscous in nature.

The overall average permeability for the rectangular specimens (excluding the 6 x 6* set) corresponds to 0.0147 SPU*. Comparison of the results for the 6 x 6 and 6 x 6* specimens indicates that the latter specimens (for which the flow was parallel to the ribbon direction) were much more permeable.

Annular Specimens

ΔP and $\Delta(P^2)$ plots for the annular specimens are given in FIG 5 and 6 for air and nitrogen and generally are consistent with those for the rectangular specimens.

To permit further interpretation, the average values for Tables II, III, and IV were cross plotted in FIG 7 to indicate relative permeabilities of the individual specimens to the different gases. Because of similarity of gas properties, the nitrogen/air plot gives little clue as to transport mechanism but indicates reproducibility of results. The

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*Permeabilities are given in standard metric units (SPU):

$$1 \text{ SPU} = \frac{(\text{Std cc})\ (\text{cm})}{(\text{sec})\ (\text{cm}^2)\ (\text{cm Hg } \Delta P)}$$

appreciable difference in properties of helium and nitrogen or air permits speculation on the major or prevailing transport mode, as shown in FIG 7 by indicating the relations expected for purely viscous and molecular flow. The experimental points fall between the lines that indicate expected behavior for molecular and viscous flow, confirming the indication that both mechanisms are operative.

An attempt was made to establish pressure profiles within one of the annular specimens by pressure measurements at 52 points during steady-state flow. The results, given in FIG 8, suggest some limited influence of ribbon direction on flow within the specimen, thus confirming the indication obtained for the rectangular specimens. This observation of greater permeability parallel to the ribbon direction indicates that face-to-face bonds within the ribbon provide some flow passages. Since all ribbon orientations are encountered by the gases permeating the annular specimens, it would be expected that such specimens would yield data representing a compromise between 6 x 6 and 6 x 6* results. This is not entirely supported by the data since comparison of results in Tables I and II shows that, in general, the annular and rectangular data are similar, average values for air being 0.0140 and 0.0147 SPU, respectively.

DISCUSSION

The flow rates and permeabilities observed indicate that transport through the honeycomb is fast enough to cause concern but too slow to permit rapid purging. In the absence of structural or other limitations, it would appear that deliberate perforation of the honeycomb would permit ready purging and therefore be a desirable modification for the hydrogen-stage Saturn common bulkheads.

From a more basic viewpoint, experimental evidence suggests that molecular flow supplemented by some viscous flow is responsible for transport of fluids within the honeycomb "sandwich" structure. Consideration of known permeation rates for the HT-424 tends to preclude permeation of the adhesive as a factor contributing substantially to the flow observed. However, it must be remembered that the HT-424 is a "filleting" or "foaming" adhesive which contains gas bubbles of easily visible size. The frequency of occurrence of these bubbles suggests the possibility of "bridging" honeycomb walls by gas bubbles in the adhesive, thus providing almost uninterrupted flow paths.

For Saturn applications, the order and mechanism of fluid flow through the LH_2 - LOX common bulkhead honeycomb core are important because of safety and reliability factors. Hazards which can be minimized by effective purging with the proper gas are:

(1) Liquid oxygen impact sensitivity problems of adhesives and other organic materials resulting from condensation of liquid oxygen from air indigenous to the bulkhead

(2) Intolerable increases of thermal conductivity caused by the presence or influx of undesirable gases (especially He and H_2)

(3) Explosive hazards resulting from the presence of oxygen (air) and the leakage of hydrogen to form a mixture, in undetermined phase, of explosive concentration

(4) Excessive or extended gradual influx of gases, particularly condensibles, during tanking and hold. Upon detanking and warmup, the evaporation rate may greatly exceed the permeation rate and, therefore, result in local pressurized areas which could impair bulkhead structural integrity.

It is evident that purging and evacuation times could be greatly decreased by use of perforated honeycomb core material. However, this would offset any advantages resulting from confining or isolating individual leaks. Further study of these factors is needed.

APPLICATION: TRANSIENT STUDY

During the early stages of this investigation, leaks were discovered in S-IV bulkheads, and a purging procedure was required to maintain internal oxygen concentrations below the lower explosive limit. Use of available data permitted recommendation of a purge and backfill cycle as outlined below. All calculations were based on results of permeation studies with air and nitrogen on the annular specimens.

The initial approach to the problem consisted of defining the system in basic laminar and molecular flow equations for radial flow within the annulus (or the flat cylinder in the case of the S-IV stages). Mathematical difficulties and the need for an immediate solution resulted in abandoning this basic approach in favor of one based on a direct and accepted analogy with heat conduction, the appropriate solutions for which were immediately available (Ref. 2 and 3) as a graph employing dimensionless variables.

One of the most critical decisions in this analysis was the choice of a permeability value which determined the mass diffusivity. Based on the results available at that time, a range of 0.01 - 0.02 SPU that resulted in diffusivities of 0.416 - 0.833 cm^2/sec was chosen. Subsequent completion of permeation experiments yielded an average permeability of 0.0140 SPU for annular honeycomb specimens using air.

Further assumptions inherent in this analogy are two dimensional isotropy (equal flow along all radii): absence of effects of upstream and downstream face plates ("end effects") and validity of the molecular flow mechanism. An equivalent diameter of 50 feet was assumed to allow for curvature of the S-IV bulkhead.

The method of calculation consisted briefly of establishing the permeability parameters analogous to heat transfer parameters and evaluating the resulting family of essentially linear relations of the form:

$$\ln\left(\frac{P' - P}{P' - P_b}\right) = f\left(\frac{D\theta}{r_m^2}\right)$$

Analogous dimensional groupings of heat and mass transfer parameters are given in Table V. FIG 9 shows calculated chronological pressure reduction profiles for a 14-inch diameter laboratory specimen and for a full sized bulkhead, both based on a permeability of 0.02 SPU and a peripheral pressure of not more than 0.5 psia during evacuation. The results indicated that evacuation to a pressure of less than three psia at all points within the bulkhead would require approximately three days. Similar calculations indicated that backfilling with nitrogen to reduce the oxygen concentration to below five percent by volume also could be accomplished in approximately three days. To afford protection against damage to the bulkhead during warmup caused by rapid expansion of gases leaking into its interior during static testing, reevacuation for a period of three days just before tanking was recommended.

To obtain confirmation for the method of calculation, unsteady state flow behavior was determined experimentally for specimens number 8-4 and 14-1 and compared with results calculated using steady-state permeabilities of 0.01 and 0.02 SPU. The results are given in FIG 10 and 11. It can be seen that the agreement between calculated and experimental results is good for both specimens, lending credence to the method of calculation.

The purging and backfilling cycles are conservative since all assumptions were in favor of low flow rates. For example, use of the molecular flow regime for calculation results in lower rates (or longer times) than would be encountered with viscous flow. Two dimensional stresses of the honeycomb material resulting from bonding between curved sheets would tend to open additional passages for gas. In these respects, the times specified for the purge cycles may be unnecessarily long; however, reduction of the times cannot be made safely without intensive additional investigation which does not appear to be warranted.

CONCLUSIONS

Room temperature studies of the flow of gases through annular and rectangular face-sealed honeycomb specimens were made for several pressure-drop levels. The results indicated an overall average permeability of approximately 0.014 SPU.

Analysis of the results suggested that molecular flow supplemented by some viscous flow is responsible for mass transport within the honeycomb structure. It also was noted that use of perforated honeycomb core material would permit greatly decreased purging and evacuation times. However, perforation of the core material would offset any advantages which might result from confining or isolating individual leakage points. Additional study of these factors is needed.

Application of these results to the problem of purging the S-IV bulkhead suggested a procedure in which the bulkhead is evacuated for three days, backfilled with gaseous nitrogen for three days, and then reevacuated for three days just before tanking with propellants.

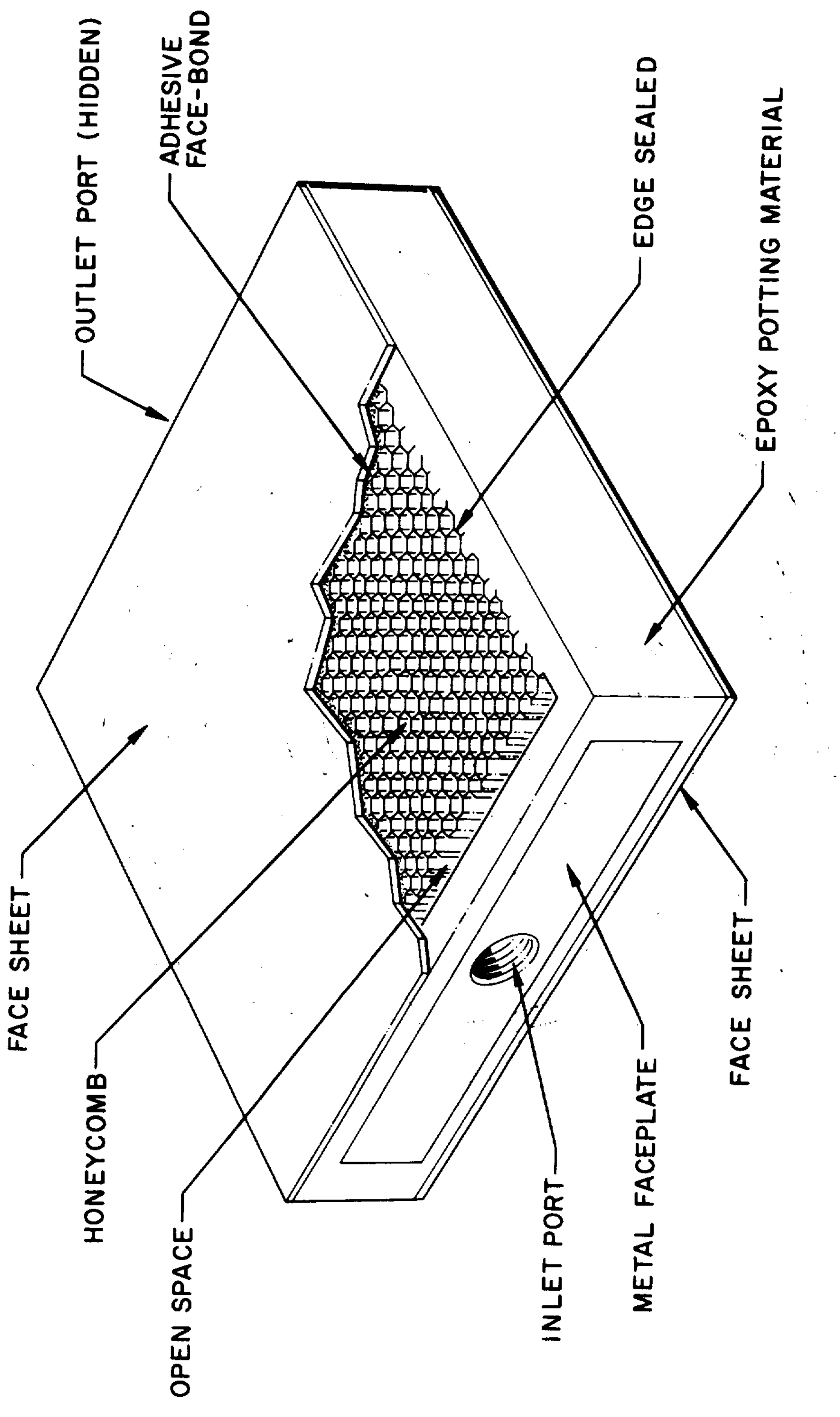


FIGURE 1. DETAILS OF RECTANGULAR HONEYCOMB SPECIMEN

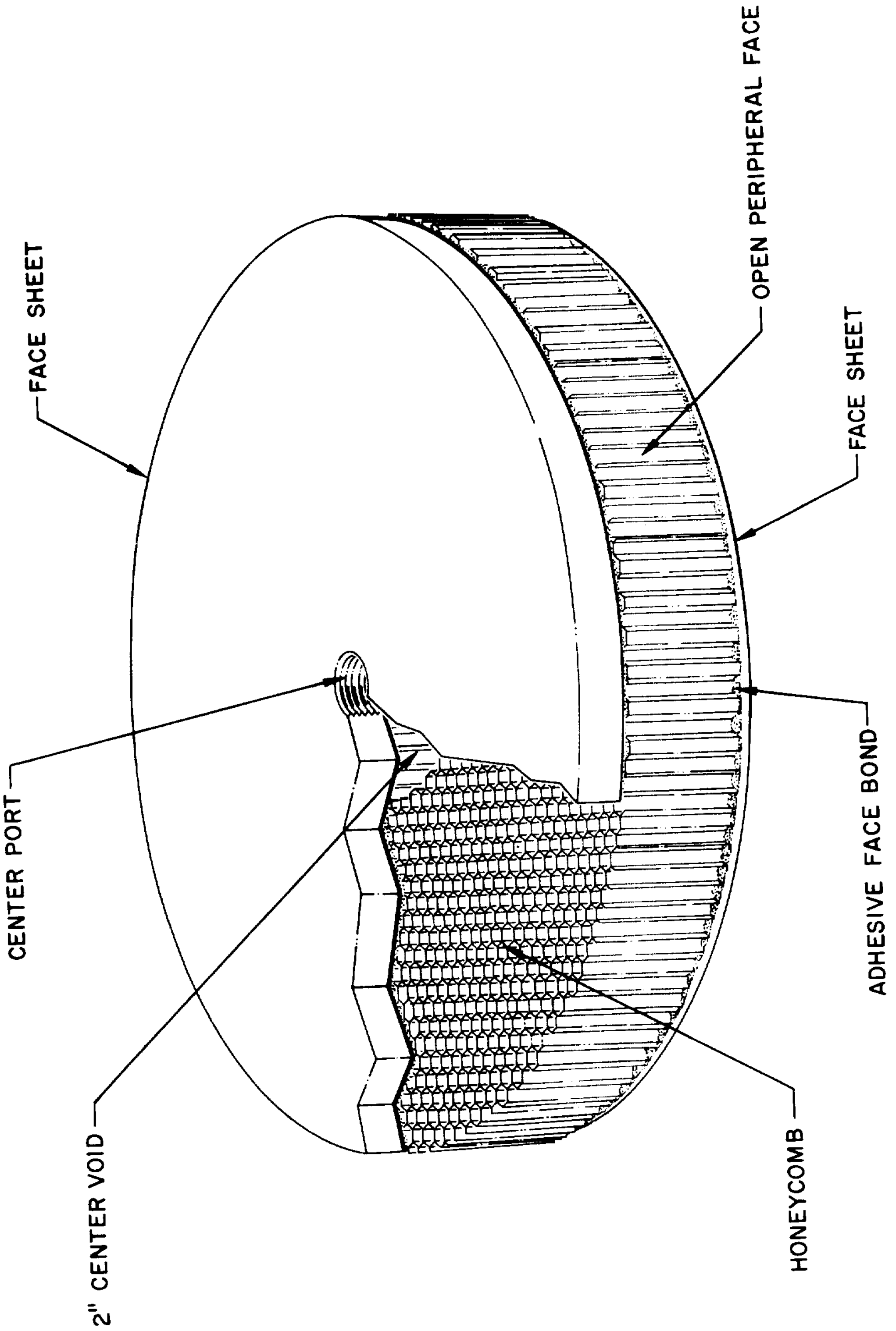
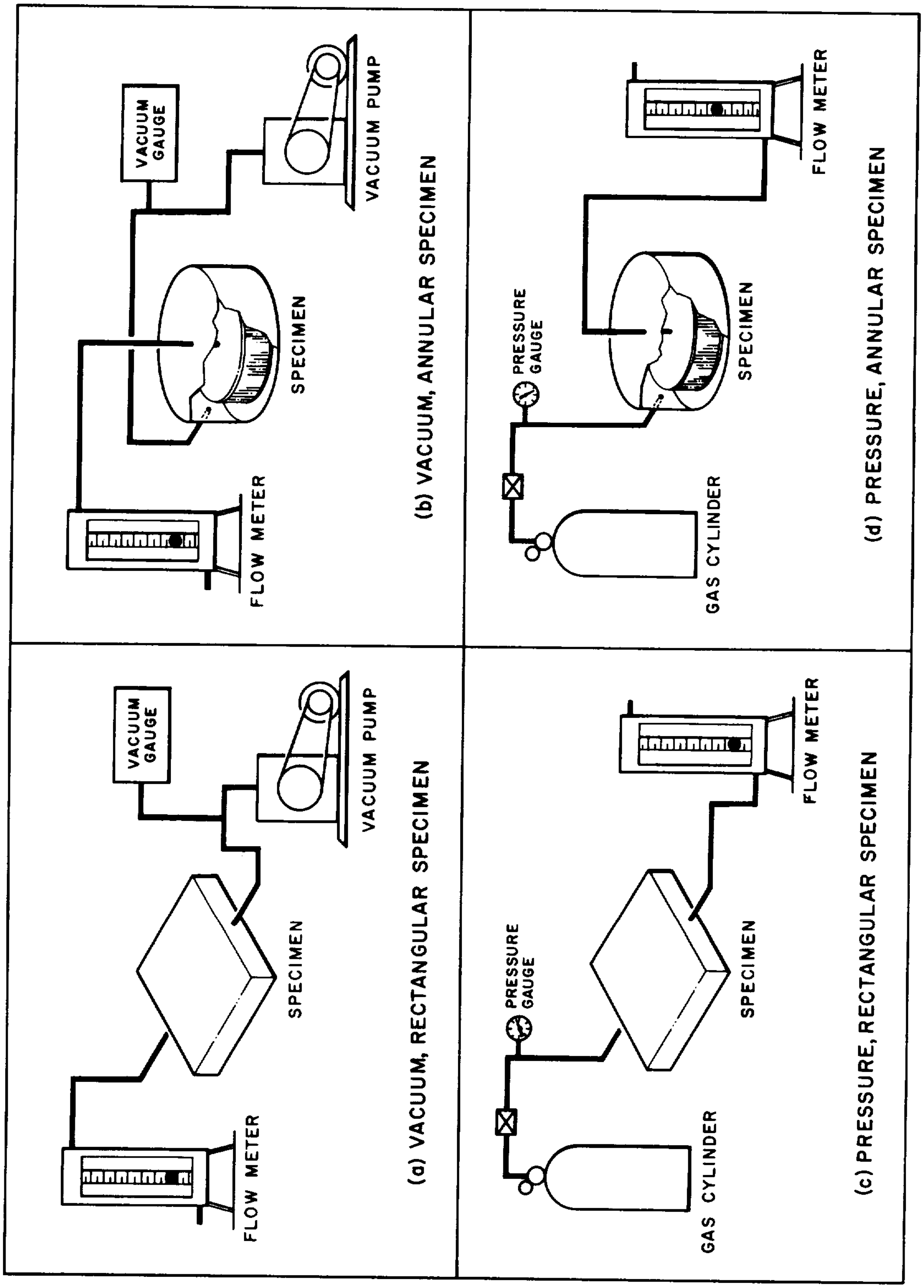


FIGURE 2. DETAILS OF ANNULAR HONEYCOMB SPECIMEN



(a) VACUUM, RECTANGULAR SPECIMEN

(b) VACUUM, ANNULAR SPECIMEN

(c) PRESSURE, RECTANGULAR SPECIMEN

(d) PRESSURE, ANNULAR SPECIMEN

FIGURE 3. DETAILS OF TEST ARRANGEMENTS

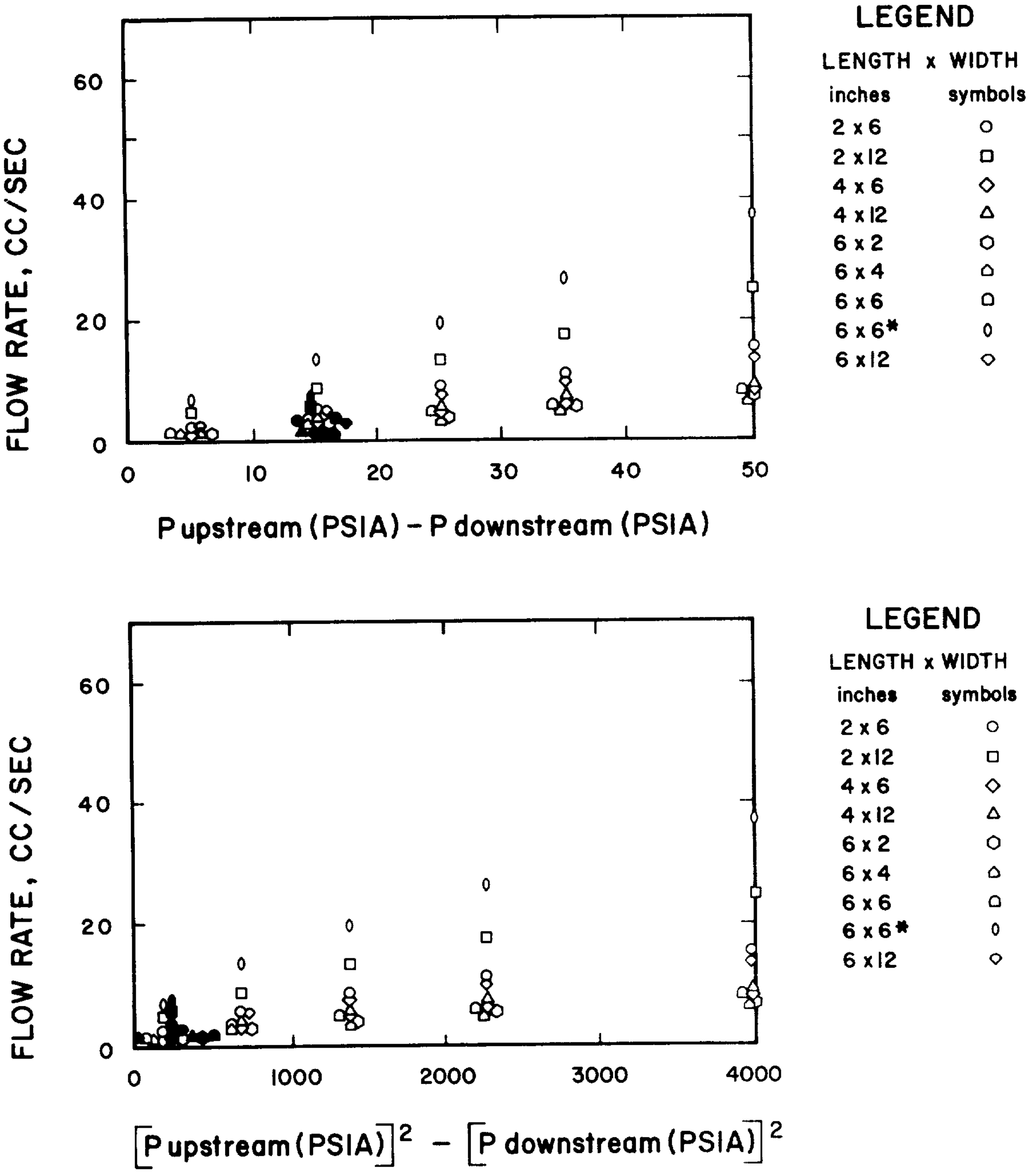


FIGURE 4. AVERAGE AIR FLOW RATES FOR RECTANGULAR SPECIMENS

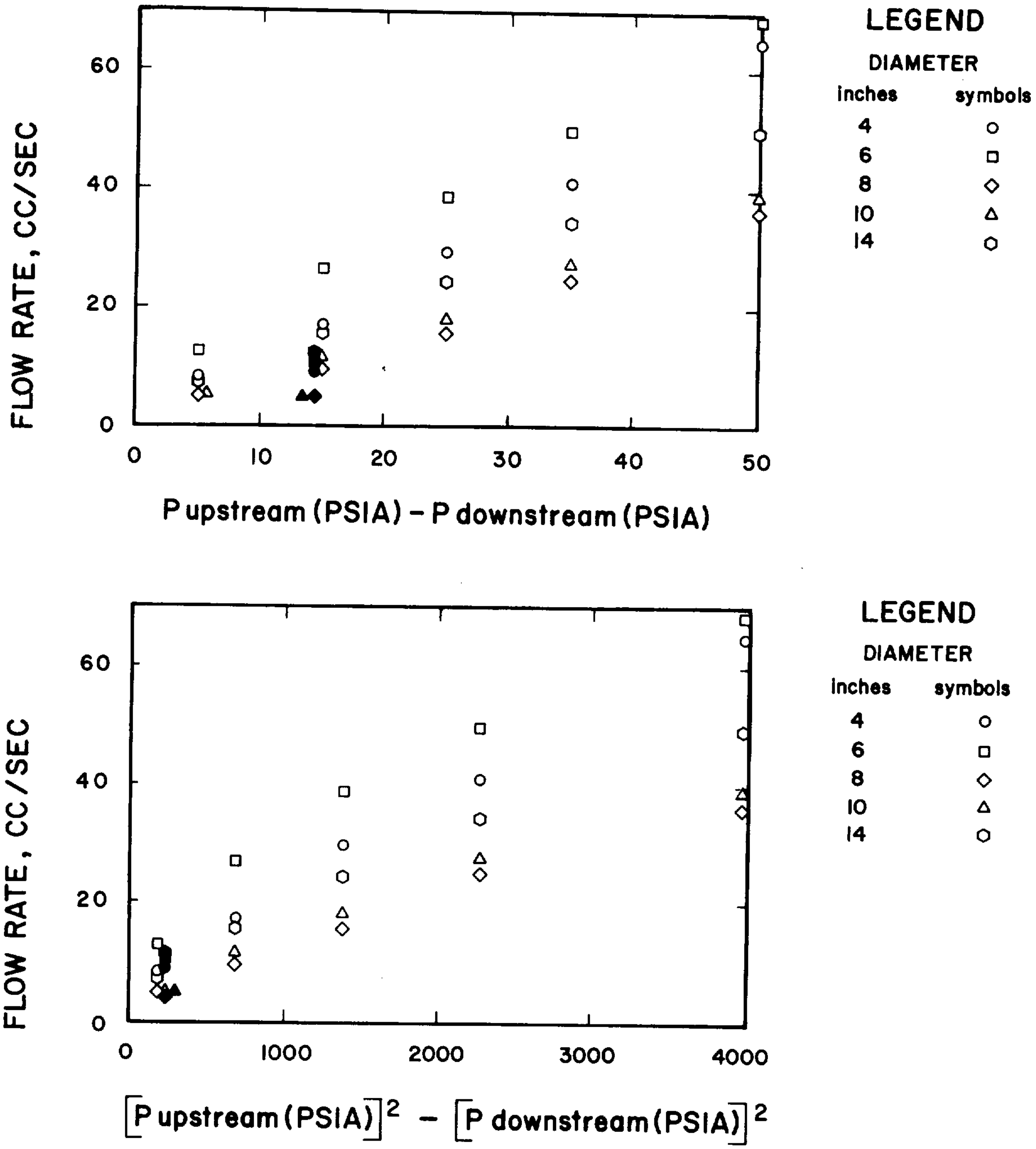


FIGURE 5. AVERAGE AIR FLOW RATES FOR ANNULAR SPECIMENS

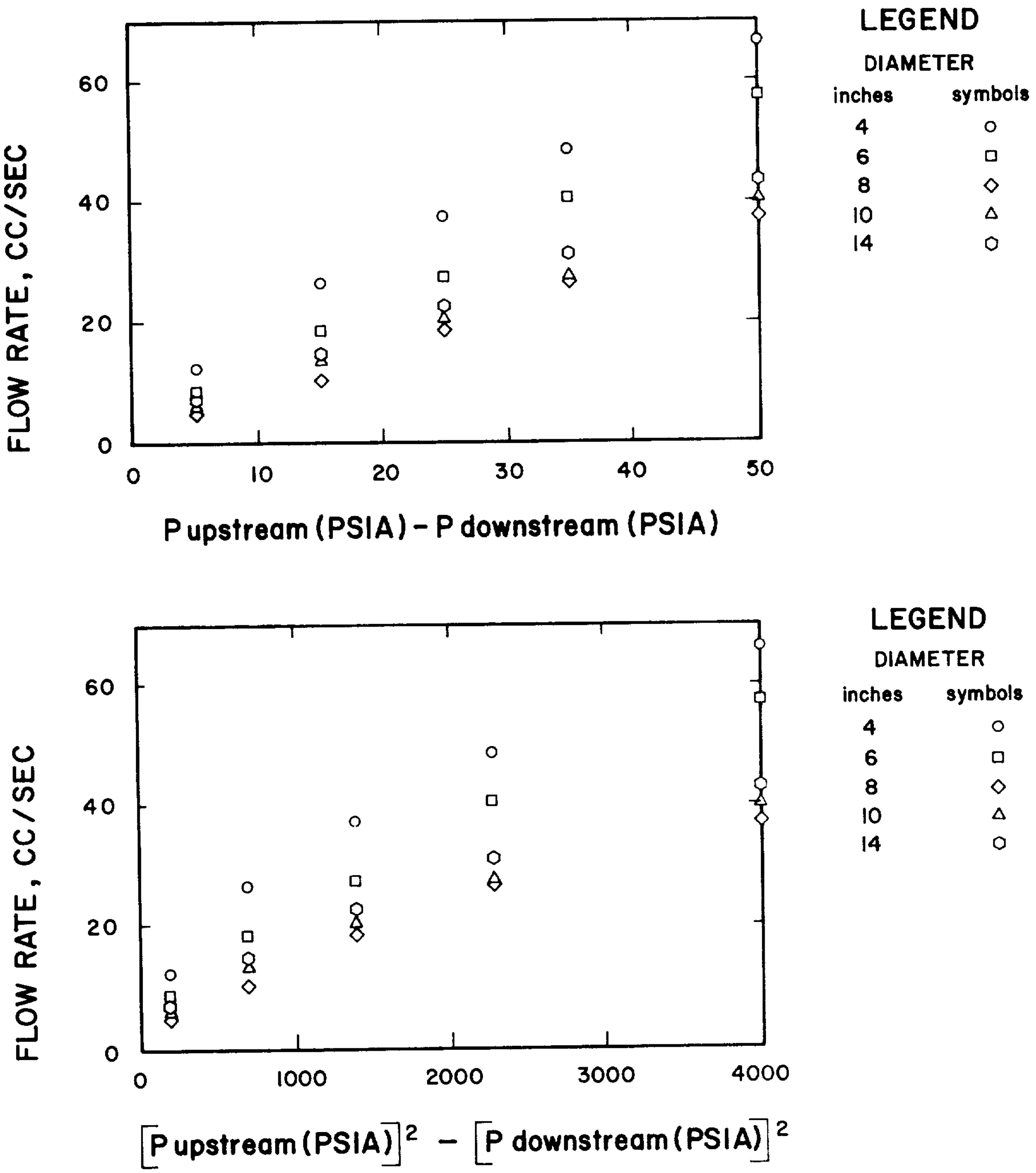


FIGURE 6. AVERAGE NITROGEN FLOW RATES FOR ANNULAR SPECIMENS

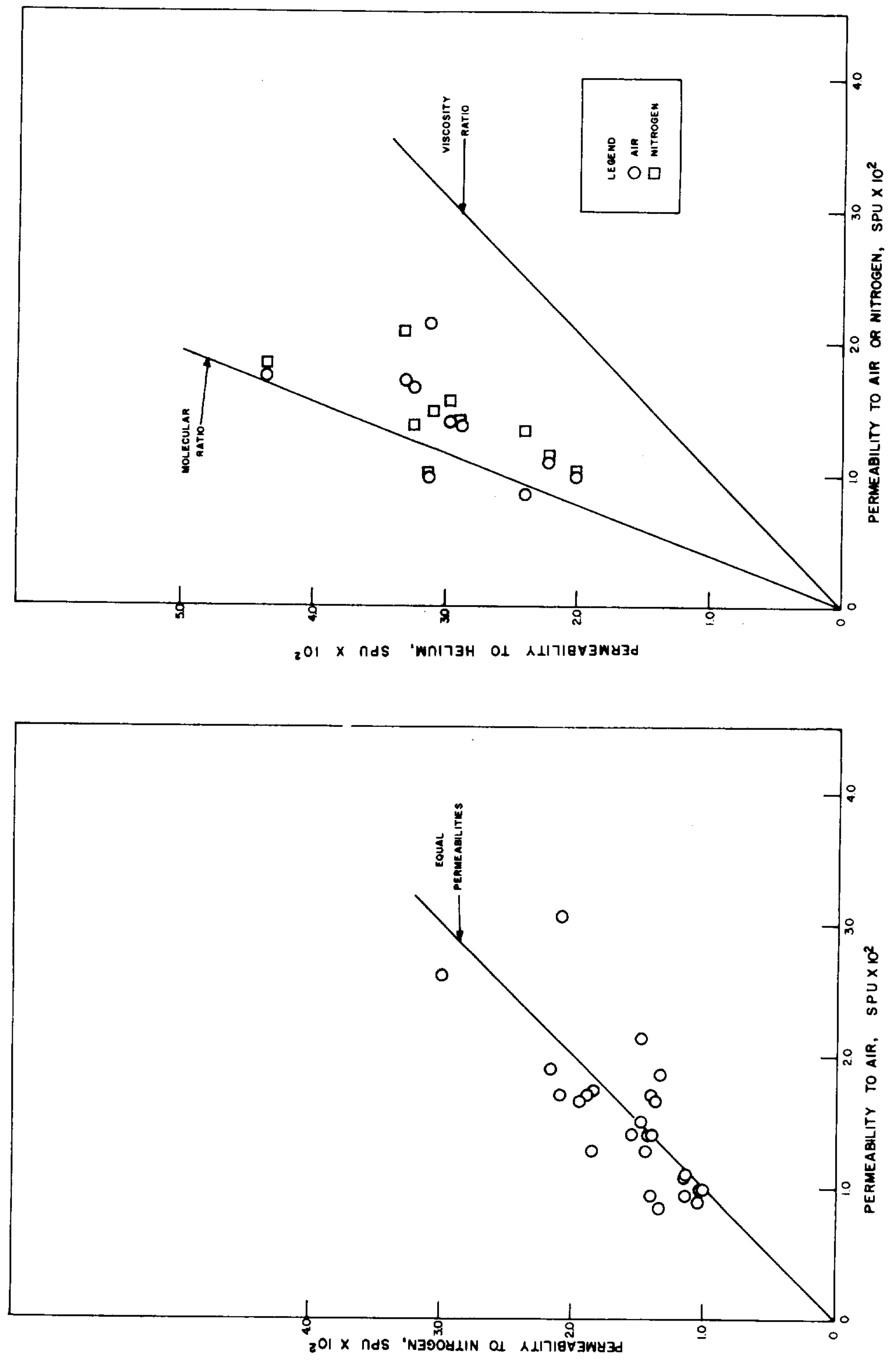


FIGURE 7. CROSS-PLOTS OF AVERAGE PERMEABILITIES TO AIR, HELIUM, AND NITROGEN

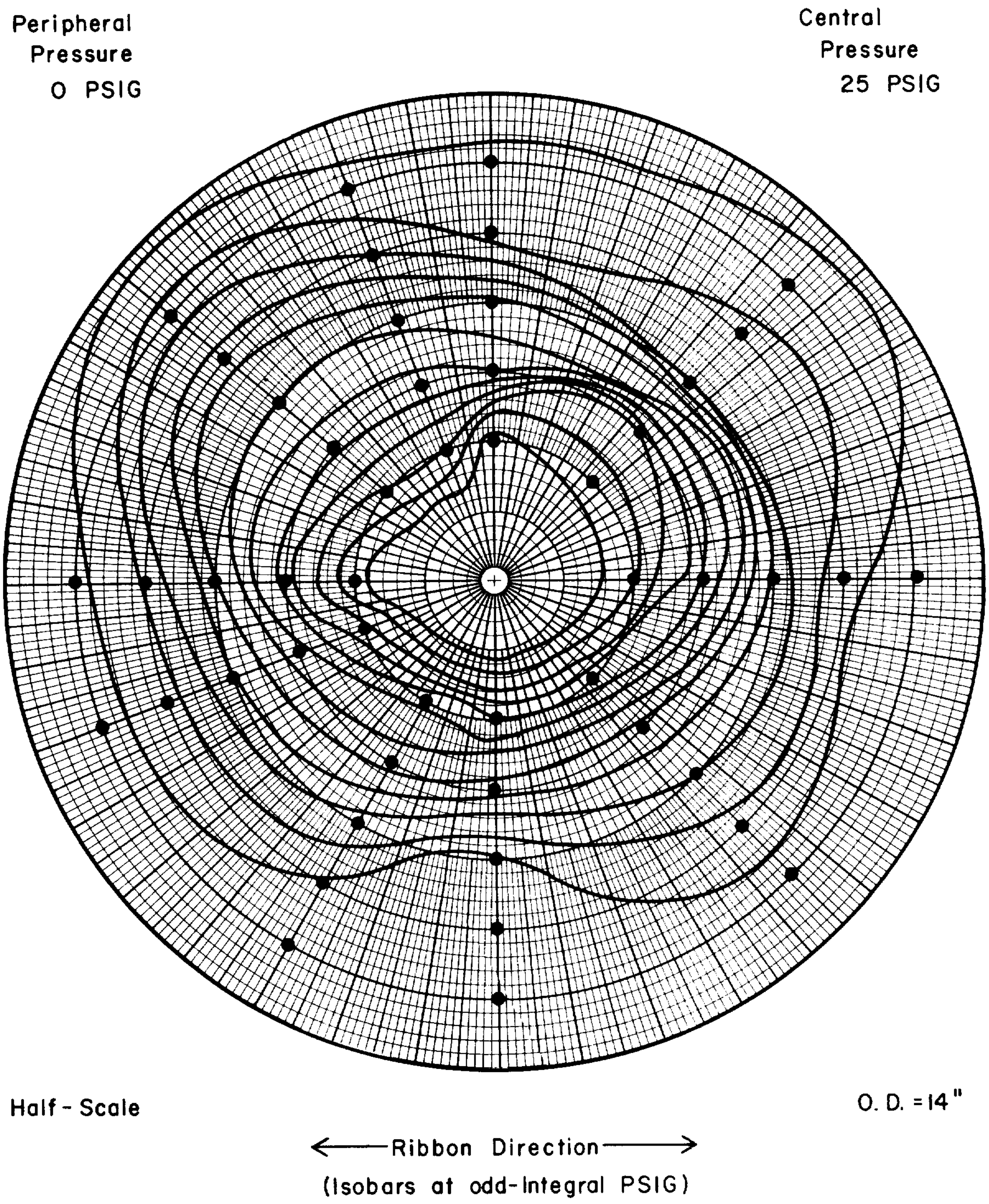


FIGURE 8. PRESSURE PROFILE DURING STEADY-STATE RADIAL AIR FLOW THROUGH ANNULAR HONEYCOMB SPECIMEN

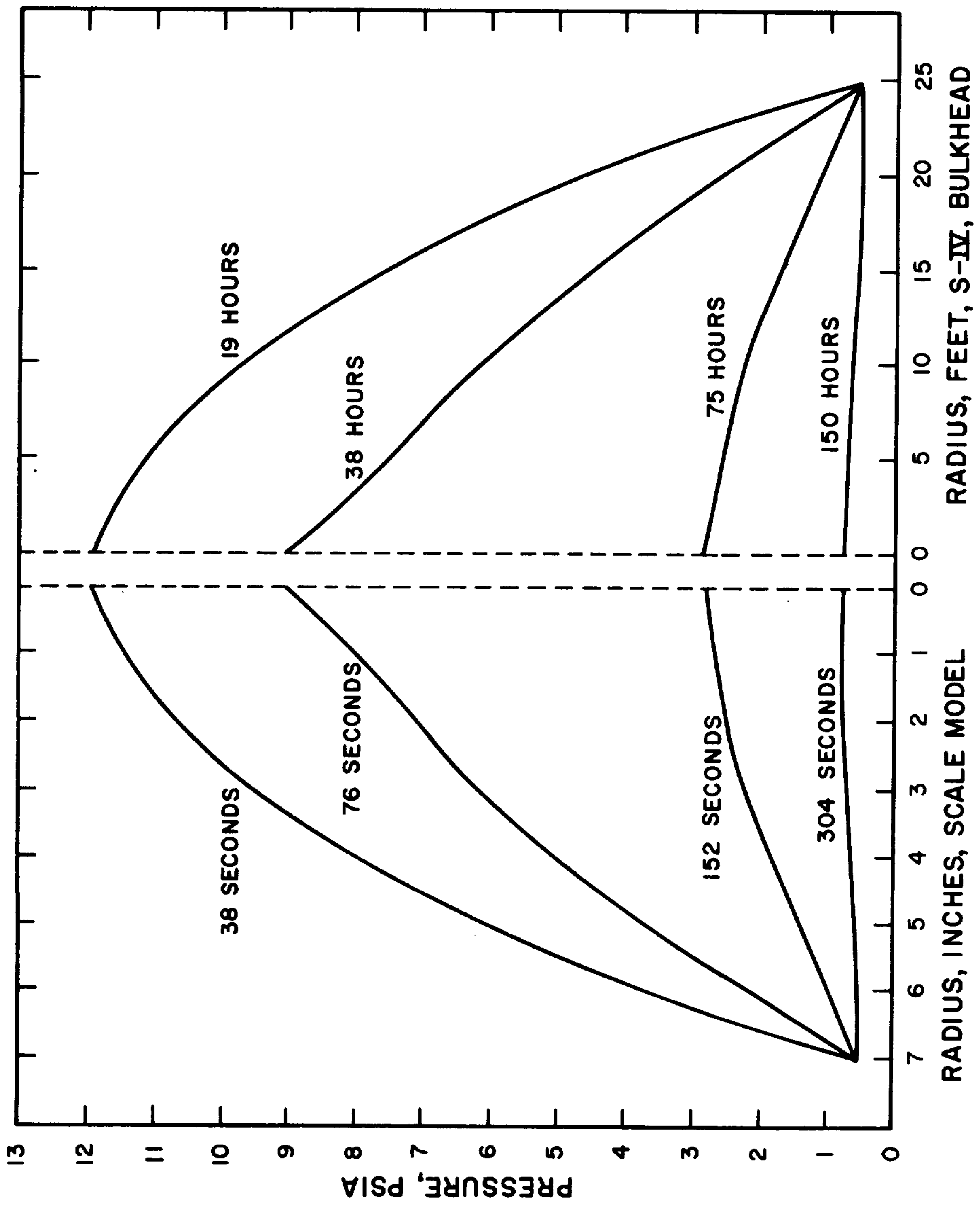


FIGURE 9. CALCULATED CHRONOLOGICAL PRESSURE REDUCTIONS FOR LABORATORY SPECIMEN AND FULL SCALE BULKHEADS

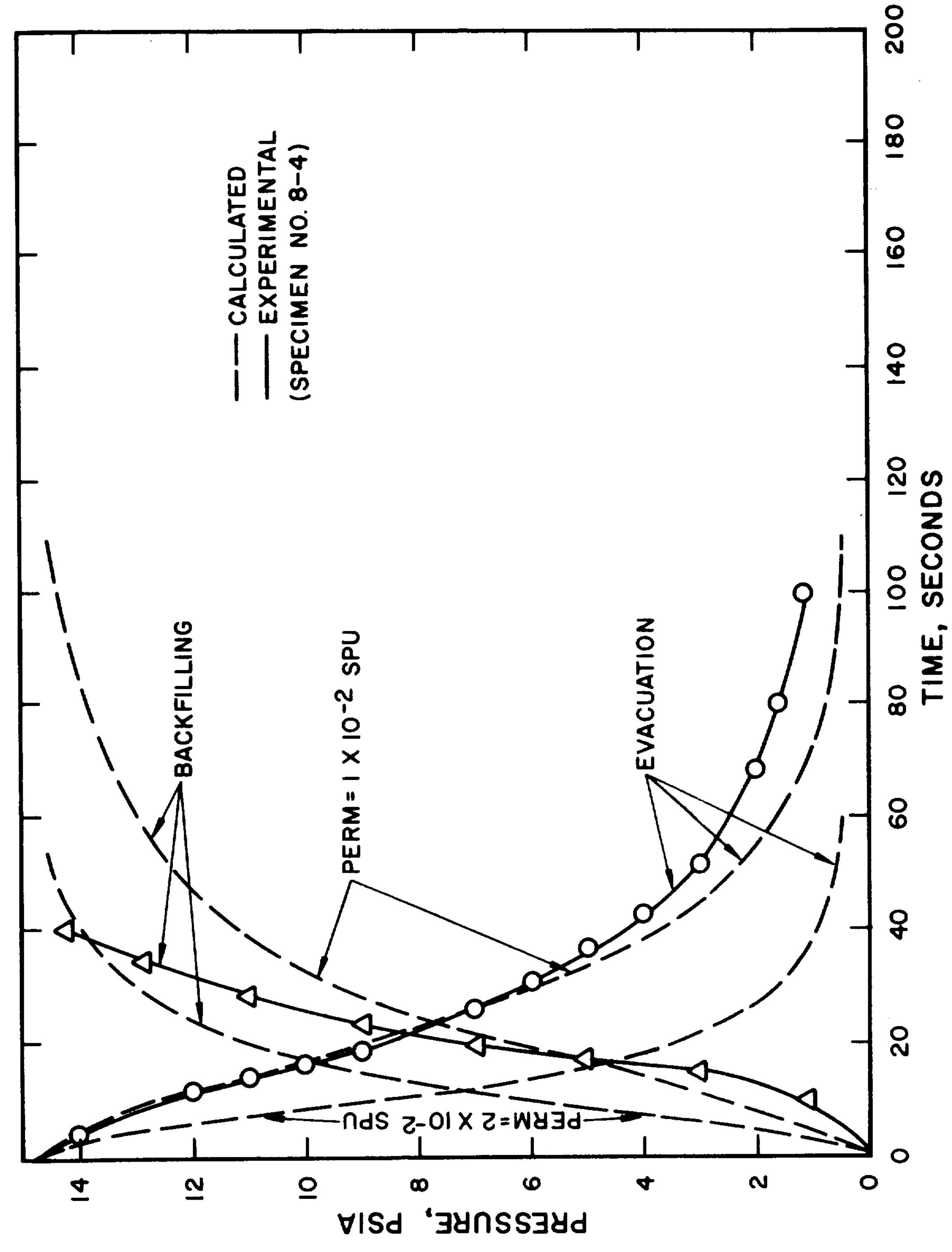


FIGURE 10. COMPARISON OF OBSERVED AND CALCULATED UNSTEADY STATE BEHAVIOR FOR 8-INCH ANNULAR SPECIMENS

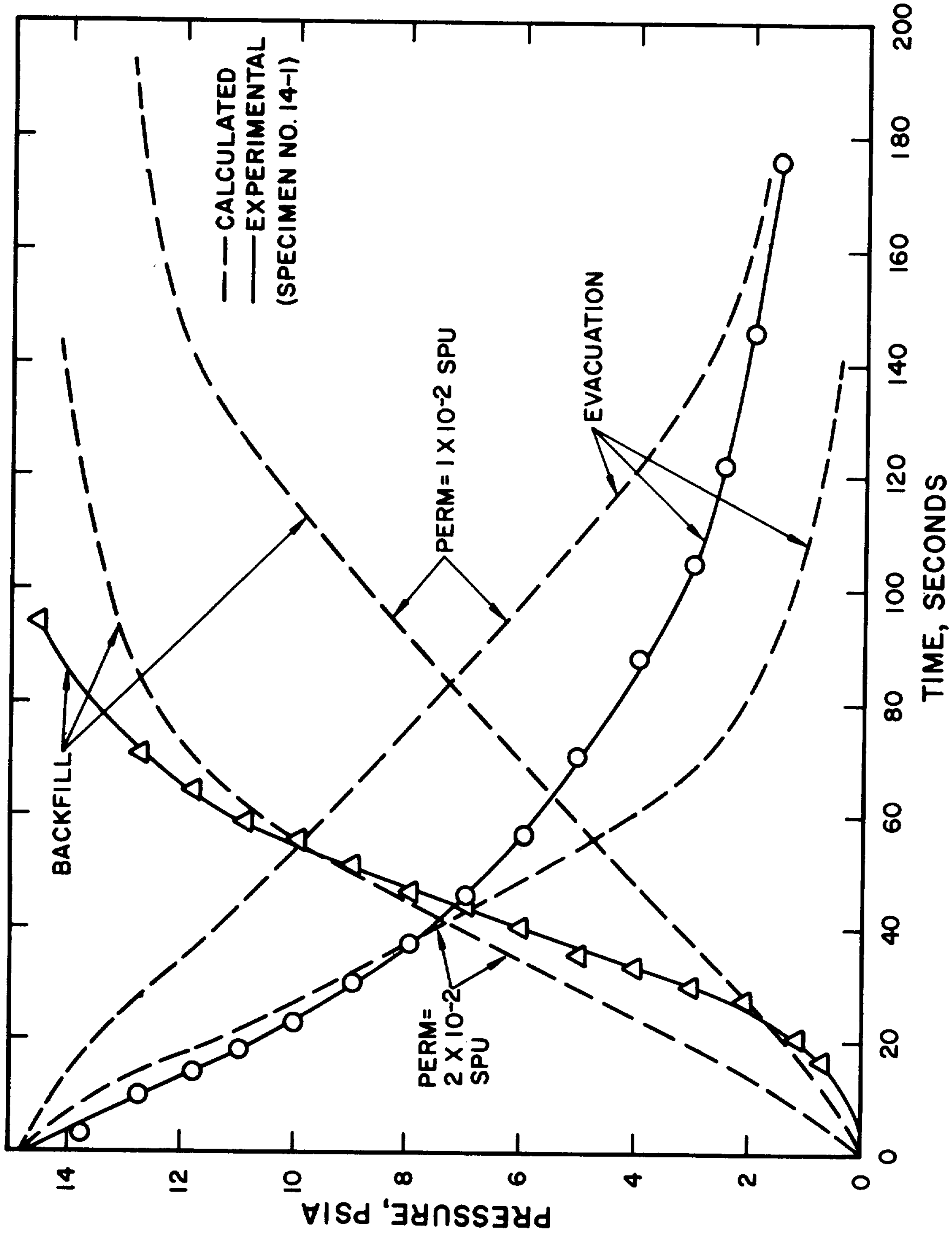


FIGURE 11. COMPARISON OF OBSERVED AND CALCULATED UNSTEADY STATE BEHAVIOR FOR 14-INCH ANNULAR SPECIMENS

TABLE I

AIR FLOW THROUGH RECTANGULAR HONEYCOMB SPECIMENS

LENGTH X WIDTH/ SPECIMEN NO.	FLOW RATE (CC/SEC) FOR INDICATED PRESSURE DROP						PERMEABILITY* × 10² FOR INDICATED PRESSURE DROP					
	VACUUM, 14.7 PSI	5 PSI	15 PSI	25 PSI	35 PSI	50 PSI	VACUUM, 14.7 PSI	5 PSI	15 PSI	25 PSI	35 PSI	50 PSI
2 X 6 / 1	2.57	.94	3.39	5.24	7.30	10.10	0.48	1.24	0.57	0.53	0.53	0.51
2	4.17	2.81	6.25	9.71	12.80	16.00	0.75	[illegible]	1.05	0.99	0.93	0.81
3	5.71	3.63	6.70	10.30	14.60	22.10	1.06	1.35	1.13	1.05	1.06	1.12
4	3.65	2.35	5.60	8.18	11.60	15.60	0.73	[illegible]	0.95	0.83	0.86	0.79
5	2.80	1.56	5.27	8.09	10.70	15.00	0.59	1.13	0.86	0.82	0.77	0.76
6	2.80	2.04	4.47	7.03	8.98	12.30	0.50	1.04	0.76	0.71	0.65	0.63
AVG	3.65	2.06	5.34	8.09	11.00	15.18	0.66	[illegible]	0.89	0.82	0.80	0.77
2 X 12 / 1	5.34	4.70	8.98	14.40	16.40	23.20	0.48	[illegible]	0.76	0.73	0.60	0.59
2	2.34	1.86	[illegible]	6.23	8.18	11.20	0.20	1.47	0.45	0.42	0.36	0.29
3	7.07	5.53	11.20	15.00	21.60	30.40	0.63	[illegible]	0.94	0.76	0.79	0.77
4	3.41	2.97	4.28	6.70	9.71	14.70	0.30	[illegible]	0.36	0.34	0.35	0.37
5	8.94	7.26	14.10	19.60	26.80	37.10	0.80	[illegible]	1.19	1.01	0.97	0.94
6	7.99	5.15	7.13	16.40	24.30	32.90	0.71	[illegible]	0.59	0.83	0.68	0.82
AVG	5.85	4.41	8.29	13.06	17.87	24.92	0.52	1.09	0.70	0.66	0.63	[illegible]
4 X 6 / 1	3.14	1.25	4.47	7.91	8.69	14.00	1.12	[illegible]	1.68	1.61	1.26	1.48
2	2.08	[illegible]	3.22	4.61	6.75	9.78	0.76	[illegible]	1.09	1.04	1.08	0.99
3	2.05	1.39	3.22	5.72	6.75	9.76	0.71	[illegible]	1.09	1.06	0.98	0.99
4	1.87	1.35	3.38	5.06	6.34	8.78	0.66	[illegible]	1.14	1.03	0.95	0.89
5	0.79	0.39	0.65	1.35	2.03	3.52	0.28	[illegible]	0.22	0.27	0.30	0.36
6	1.87	0.78	2.59	3.52	5.22	8.60	0.66	0.79	0.71	0.71	0.76	0.87
AVG	1.97	1.22	2.92	4.61	6.00	9.18	0.70	[illegible]	0.99	0.94	0.87	0.93
4 X 12 / 1	2.11	1.85	3.73	5.20	6.82	9.29	0.38	[illegible]	0.63	0.53	0.49	0.47
2	2.11	1.88	3.80	5.71	7.47	10.40	0.37	[illegible]	0.64	0.58	0.54	0.53
3	1.68	3.37	9.10	10.60	14.20	15.50	0.30	1.21	1.54	1.07	1.03	0.79
4	2.08	2.09	4.20	5.82	7.38	9.80	0.37	[illegible]	0.69	0.59	0.54	0.50
5	1.40	0.60	1.26	3.38	5.00	7.01	0.25	0.30	0.20	0.34	0.36	0.36
6	1.12	0.89	1.89	2.53	3.50	4.19	0.20	0.32	0.32	0.26	0.24	0.21
AVG	1.75	1.78	3.96	5.54	7.39	9.37	0.31	0.96	0.67	0.56	0.54	0.45
6 X 2 / 2	0.74	0.66	1.18	2.06	2.63	[illegible]	1.15	[illegible]	1.80	1.88	1.73	1.67
3	3.77	3.17	5.02	9.22	12.70	15.70	5.94	[illegible]	7.78	8.42	8.10	7.19
4	0.79	0.50	1.04	1.57	2.06	3.33	1.24	[illegible]	1.55	1.44	1.37	1.52
5	1.57	0.96	2.06	3.05	4.66	7.21	2.49	[illegible]	2.44	2.79	3.04	3.29
AVG	1.72	1.32	2.33	3.98	5.52	7.45	2.72	[illegible]	3.40	3.63	3.61	3.40
6 X 4 / 1	2.79	2.20	4.98	7.30	9.43	12.56	[illegible]	[illegible]	3.79	3.33	3.56	2.86
2	1.68	1.49	3.15	4.79	5.60	7.39	2.37	[illegible]	2.36	2.15	1.83	1.69
3	2.08	1.61	3.39	4.98	6.70	11.10	1.62	[illegible]	2.58	2.18	2.18	2.53
4	0.35	0.25	0.58	0.45	0.72	1.13	0.58	[illegible]	0.55	0.21	0.24	0.26
5	0.42	0.35	0.90	0.74	1.07	1.45	0.32	[illegible]	0.58	0.34	0.35	0.34
6	0.90	0.59	1.09	1.80	2.52	3.72	0.72	[illegible]	0.83	0.82	0.71	0.86
AVG	1.37	1.08	2.32	3.33	4.34	6.23	[illegible]	[illegible]	1.71	1.52	1.40	1.47
6 X 6 / 1		0.23	0.50	0.89	1.15	1.56		[illegible]	0.25	0.27	0.25	0.30
2	1.28	1.22	2.65	4.39	4.92	6.56	0.69	[illegible]	1.13	1.05	1.07	1.00
3	1.67	0.96	2.23	4.14	5.67	7.96	[illegible]	[illegible]	1.12	.96	1.23	1.21
4	0.78	0.50	1.67	2.63	3.53	5.37	[illegible]	[illegible]	0.65	0.90	0.77	0.81
5	4.28	3.55	7.75	12.30	14.60	19.90	[illegible]	[illegible]	[illegible]	3.44	3.18	3.03
6	1.67	1.12	2.78	4.14	5.67	7.87	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
AVG	1.94	1.27	3.00	4.42	5.92	8.27	[illegible]	[illegible]	1.32	1.34	[illegible]	[illegible]
6 X 6** / 1	4.29	4.07	[illegible]	11.40	15.20	20.00	[illegible]	[illegible]	[illegible]	1.48	[illegible]	[illegible]
2	6.72	5.57	11.90	17.80	[illegible]	[illegible]	1.79	[illegible]	6.04	5.43	[illegible]	[illegible]
3	5.70	5.09	10.50	15.40	[illegible]	[illegible]	1.27	[illegible]	5.31	4.68	[illegible]	[illegible]
4	11.00	10.70	20.00	29.20	39.10	57.60	[illegible]	[illegible]	[illegible]	9.58	8.52	8.76
5	8.12	7.50	15.60	21.50	29.50	40.70	[illegible]	[illegible]	7.93	6.54	6.52	[illegible]
6	7.97	7.50	[illegible]	21.50	28.50	40.10	[illegible]	[illegible]	7.49	5.54	6.16	[illegible]
AVG	7.30	6.74	13.64	19.47	26.32	[illegible]	[illegible]	[illegible]	[illegible]	5.76	5.73	[illegible]
6 X 12 / 1	3.12	2.54	[illegible]	8.09	10.30	15.20	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2	4.91	4.28	[illegible]	13.60	18.60	25.60	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3	1.18	1.15	[illegible]	5.53	4.77	6.61	[illegible]	[illegible]	0.52	[illegible]	0.52	0.45
4	-	[illegible]	4.91	7.16	9.35	12.50	-	[illegible]	[illegible]	1.09	[illegible]	0.59
5	1.07	[illegible]	[illegible]	4.91	[illegible]	8.81	[illegible]	[illegible]	[illegible]	0.72	0.73	0.63
6	2.78	1.55	5.37	7.87	10.00	13.60	0.72	[illegible]	[illegible]	[illegible]	[illegible]	1.04
AVG	2.61	[illegible]	[illegible]	[illegible]	9.96	13.30	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
12 X 2 / 1	0.45	0.60	1.17	2.09	3.15	4.34	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2	0.56	[illegible]	1.11	1.46	1.79	2.61	[illegible]	[illegible]	3.36	2.70	2.34	[illegible]
3	0.35	0.30	[illegible]	0.54	0.65	1.14	[illegible]	[illegible]	[illegible]	0.95	[illegible]	1.04
5		0.22	[illegible]	0.47	0.49	0.67		[illegible]	1.05	0.73	[illegible]	0.61
6	0.94	0.49	1.56	1.94	2.61	4.26	[illegible]	[illegible]	3.52	[illegible]	[illegible]	3.85
AVG	0.58	0.42	0.91	1.29	1.73	2.61	1.76	[illegible]	2.57	2.36	2.26	2.38
12 X 4 / 1	0.34	0.35	[illegible]	0.75	1.16	1.61	[illegible]	[illegible]	0.75	0.65	[illegible]	0.74
3	0.93	0.55	[illegible]	1.94	2.34	3.37	[illegible]	[illegible]	1.57	1.72	[illegible]	[illegible]
5	0.99	0.87	[illegible]	2.76	4.12	5.75	[illegible]	[illegible]	1.82	[illegible]	[illegible]	[illegible]
AVG	0.75	0.59	1.12	1.82	2.31	3.64	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
12 X 6 / 2	0.65	0.33	1.10	1.12	2.09	2.61	[illegible]	[illegible]	[illegible]	0.71	0.91	0.79
3	0.22	0.30	0.58	0.64	0.88	1.14	[illegible]	[illegible]	[illegible]	0.39	[illegible]	[illegible]
4	0.70	[illegible]	[illegible]	1.48	1.79	3.37	[illegible]	[illegible]	[illegible]	0.90	0.74	[illegible]
5	0.43	0.34	[illegible]	1.12	1.61	2.09	0.47	[illegible]	0.71	0.71	0.70	[illegible]
6	1.14	[illegible]	1.05	2.76	3.73	5.75	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.76
AVG	0.63	0.45	1.06	1.44	2.02	3.00	[illegible]	[illegible]	1.07	0.85	0.88	0.91

* Permeability given in standard metric units (SPU)

$$1 \text{ SPU} = \frac{(\text{Std cc})\ (\text{cm})}{(\text{sec})\ (\text{cm}^2)\ (\text{cm Hg } \Delta P)}$$

** Specimens have flow parallel with ribbon direction; all others have flow normal to ribbon direction.

TABLE II

AIR FLOW THROUGH ANNULAR HONEYCOMB SPECIMENS (I.D. = 2")

OUTSIDE DIAMETER/ SPECIMEN NO.	FLOW RATE CC/SEC FOR INDICATED PRESSURE DROP						PERMEABILITY* X 10^2 FOR INDICATED PRESSURE DROP					
	VACUUM, 14.7 PSI	5 PSI	15 PSI	25 PSI	35 PSI	50 PSI	VACUUM, 14.7 PSI	5 PSI	15 PSI	25 PSI	35 PSI	50 PSI
4 / 1	3.9	5.0	11.6	23.3	28.7	43.3	0.20	0.76	0.59	0.71	0.63	0.66
2	7.9	5.9	11.8	25.1	34.6	58.9	0.42	0.90	0.63	0.76	0.75	0.90
3	13.8	9.3	20.1	35.6	47.4	84.0	0.73	1.40	1.01	1.08	1.03	1.27
4	11.8	9.8	20.1	28.7	37.9	54.8	0.62	1.48	1.01	0.88	0.82	0.83
5	8.8	9.8	20.1	32.9	48.4	67.1	0.46	1.48	1.01	1.00	1.05	1.02
6	8.2	10.9	18.7	32.4	47.4	82.1	0.43	1.65	0.95	0.99	1.03	1.25
AVG	9.1	8.5	17.1	29.7	40.7	65.0	0.48	1.28	0.87	0.90	0.89	0.99
6 / 1	10.4	11.4	25.5	36.0	46.2	62.3	0.87	2.75	2.05	1.73	1.59	1.50
2	7.8	8.9	18.2	27.7	36.0	49.3	0.64	2.15	1.46	1.33	1.24	1.18
3	13.6	17.8	36.0	52.0	67.1	94.0	0.11	4.29	2.89	2.51	2.31	2.26
AVG	10.6	12.7	26.6	38.6	49.8	68.5	0.54	3.06	2.13	1.86	1.71	1.65
8 / 1	4.4	4.3	8.3	12.0	24.5	34.0	0.46	1.31	0.84	0.73	1.06	1.03
2	4.5	6.1	11.8	18.4	26.4	39.6	0.48	1.85	1.19	1.12	1.14	1.20
3	4.5	5.0	9.8	14.8	24.5	34.0	0.47	1.51	0.99	0.90	1.06	1.03
4	6.6	6.7	13.6	23.6	36.8	54.7	0.70	2.04	1.38	1.43	1.60	1.66
5	1.8	3.2	6.1	9.1	12.7	22.7	0.19	0.96	0.62	0.56	0.55	0.69
6	4.8	4.6	9.2	14.9	24.1	32.6	0.51	1.38	0.93	0.91	1.04	0.99
AVG	4.4	5.0	9.8	15.5	24.8	36.3	0.47	1.51	0.99	0.94	1.08	1.10
10 / 1	5.1	6.7	17.2	24.3	32.9	42.9	0.63	2.35	2.02	1.71	1.66	1.51
2	4.5	6.6	13.9	21.9	27.7	41.5	0.56	2.32	1.60	1.55	1.39	1.46
3	0.8	3.8	7.5	11.1	15.2	26.7	-	1.32	0.89	0.78	0.77	0.94
4	6.7	3.6	7.8	12.5	23.4	32.4	0.83	1.27	0.91	0.88	1.18	1.14
5	2.5	2.8	5.8	10.2	26.9	36.3	0.31	0.97	0.68	0.72	1.35	1.28
6	8.2	8.4	18.9	27.8	39.6	55.2	1.03	2.97	2.22	1.96	2.00	1.95
AVG	4.6	5.3	11.8	18.0	27.6	39.2	0.67	1.87	1.39	1.27	1.39	1.38
14 / 1	13.4	7.8	15.6	25.2	31.6	43.7	2.03	3.29	2.20	2.16	1.94	1.87
2	13.0	7.5	14.3	24.3	32.0	44.6	1.97	3.20	2.04	2.07	1.95	1.89
3	13.5	5.6	11.8	21.9	31.0	45.8	2.05	2.62	1.67	1.87	1.89	1.95
4	10.3	4.2	8.4	13.7	20.0	30.0	1.54	1.80	1.20	1.16	1.22	1.28
5	7.9	3.8	7.1	11.5	19.1	26.7	1.18	1.61	1.00	0.98	1.16	1.14
6	9.3	7.3	14.9	20.5	34.3	52.0	1.39	3.11	2.12	1.75	2.09	2.22
AVG	11.2	6.0	12.0	19.5	28.0	40.5	1.69	2.61	1.71	1.67	1.71	1.73

* Permeability given in standard metric units (SPU)

$$1 \text{ SPU} = \frac{(\text{Std cc})\ (\text{cm})}{(\text{sec})\ (\text{cm}^2)\ (\text{cm Hg } \Delta P)}$$

TABLE III

NITROGEN FLOW THROUGH ANNULAR HONEYCOMB SPECIMENS (I.D. = 2")

OUTSIDE DIAMETER/ SPECIMEN NO.	FLOW RATE CC/SEC FOR INDICATED PRESSURE DROP					PERMEABILITY* X 10^2 FOR INDICATED PRESSURE DROP				
	5 PSI	15 PSI	25 PSI	35 PSI	50 PSI	5 PSI	15 PSI	25 PSI	35 PSI	50 PSI
4 / 1	7.6	15.8	24.2	30.5	43.8	1.15	0.80	0.74	0.66	0.67
2	8.8	23.7	33.3	44.3	57.5	1.33	1.20	1.01	0.96	0.88
3	12.3	26.9	39.7	51.5	70.3	1.87	1.36	1.20	1.12	1.07
5	13.4	29.2	40.6	51.5	69.8	2.04	1.48	1.23	1.12	1.06
6	19.6	36.5	49.3	65.2	91.3	2.98	1.85	1.50	1.41	1.38
AVG	12.3	26.4	37.4	48.6	66.5	1.87	1.34	1.14	1.05	1.01
6 / 1	8.7	23.7	34.6	47.0	64.3	2.08	1.90	1.67	1.62	1.55
2	7.2	13.7	24.2	37.0	49.3	1.72	1.10	1.16	1.27	1.18
3	12.9	34.6	50.2	66.2	89.9	3.11	2.78	2.42	2.28	2.16
4	3.0	5.8	9.8	14.4	26.4	0.72	0.46	0.47	0.49	0.64
5	10.5	20.1	28.7	41.1	64.8	2.52	1.61	1.38	1.41	1.56
6	10.2	12.8	18.2	36.5	50.2	2.45	1.02	0.88	1.25	1.21
AVG	8.8	18.5	27.6	40.4	57.5	2.10	1.48	1.33	1.39	1.38
8 / 1	5.6	11.1	17.5	23.6	33.0	1.70	1.12	1.06	1.02	1.00
2	4.2	9.1	23.6	33.0	41.1	1.28	0.92	1.43	1.43	1.25
3	4.6	9.0	14.2	27.4	36.3	1.38	0.91	0.87	1.19	1.10
4	6.1	13.6	31.1	40.6	58.0	1.85	1.38	1.89	1.76	1.76
5	3.6	6.9	9.8	13.3	22.7	1.10	0.70	0.59	0.58	0.69
6	5.1	10.7	15.7	22.2	32.6	1.56	1.08	0.95	0.96	0.99
AVG	4.9	10.1	18.7	26.7	37.3	1.48	1.02	1.13	1.16	1.13
10 / 1	4.8	10.0	20.5	28.8	43.4	1.70	1.17	1.44	1.45	1.53
2	8.6	17.2	25.3	33.9	48.0	3.03	2.02	1.78	1.70	1.69
3	3.8	8.3	11.4	15.2	25.8	1.32	0.97	0.81	0.77	0.91
4	6.2	12.9	19.4	25.3	33.9	2.18	1.51	1.36	1.27	1.19
5	4.7	9.1	13.5	19.8	31.6	1.65	1.07	0.95	1.00	1.11
6	8.7	22.2	31.6	43.4	57.6	3.06	2.61	2.23	2.19	2.03
AVG	6.1	13.3	20.3	27.7	40.1	2.16	1.56	1.43	1.40	1.41
14 / 1	5.6	10.9	19.6	24.1	41.5	2.38	1.55	1.67	1.47	1.77
2	7.0	14.6	24.0	33.5	43.9	2.99	2.07	2.05	2.04	1.87
3	9.2	20.0	29.6	39.6	53.8	3.91	2.85	2.52	2.41	2.28
4	5.5	11.1	18.1	24.8	34.8	2.33	1.57	1.54	1.51	1.48
5	5.3	10.6	15.3	23.4	29.6	2.27	1.50	1.31	1.42	1.26
6	9.8	21.0	30.0	40.5	55.8	4.19	2.99	2.56	2.47	2.38
AVG	7.1	14.7	22.8	31.0	43.2	3.01	2.09	1.94	1.89	1.84

* Permeability given in standard metric units (SPU)

$$1 \text{ SPU} = \frac{(\text{Std cc})\ (\text{cm})}{(\text{sec})\ (\text{cm}^2)\ (\text{cm Hg } \Delta P)}$$

TABLE IV

HELIUM FLOW THROUGH ANNULAR HONEYCOMB SPECIMENS (I.D. = 2")

OUTSIDE DIAMETER SPECIMEN NO.	FLOW RATE (CC/SEC) FOR INDICATED PRESSURE DROP		PERMEABILITY* X 10^2 FOR INDICATED PRESSURE DROP	
	15 PSI	50 PSI	15 PSI	50 PSI
4 / 1	25.95	106.10	1.31	1.61
2	37.78	125.20	1.91	1.90
3	64.18	164.40	3.25	2.50
5	45.97	163.00	2.33	6.20
6	62.37	223.50	3.16	3.40
AVG	47.25	156.44	2.39	3.12
6 / 1	35.05	94.69	2.81	2.28
2	30.03	107.40	2.41	2.59
3	91.05	297.30	7.32	7.17
4	15.47	56.45	1.24	1.36
5	39.60	145.70	3.18	3.51
6	20.93	105.20	1.68	2.53
AVG	38.69	134.46	3.11	3.24
8 / 1	20.93	42.33	2.12	1.28
2	15.02	85.14	1.52	2.59
3	21.38	68.73	2.17	2.09
4	28.67	136.60	2.91	4.15
5	10.47	46.43	1.06	1.41
6	22.30	61.45	2.26	1.87
AVG	19.80	73.45	2.01	2.23
10 / 1	25.03	89.69	2.95	3.17
2	35.97	91.05	4.23	3.21
3	15.47	40.97	1.82	1.44
4	18.20	67.83	2.14	2.39
5	23.22	75.57	2.73	2.67
6	34.13	124.30	4.02	4.39
AVG	25.34	81.57	2.98	2.88
14 / 1	30.50	106.10	4.34	4.53
2	25.48	102.90	3.63	4.39
3	27.76	122.40	3.95	5.27
4	14.10	86.95	2.00	3.71
5	18.65	71.93	2.65	3.07
6	23.22	121.10	3.30	5.17
AVG	23.29	101.90	3.31	4.36

* Permeability given in standard metric units (SPU)

$$1 \text{ SPU} = \frac{(\text{Std cc})\ (\text{cm})}{(\text{sec})\ (\text{cm}^2)\ (\text{cm Hg } \Delta P)}$$

TABLE V

ENERGY/MASS TRANSPORT ANALOGY (For Heat Conduction and Molecular Flow)

Dimensionless Ratio	Form for Heat	Form for Mass	Comments
Y	$\frac{t' - t}{t' - t_b}$	$\frac{P' - P}{P' - P_b}$	Mass ratio usually given in concentration units; however, for ideal gas, pressure ratio is equivalent.
X	$\frac{K}{\rho c_p} \frac{\theta}{r_m^2}$	$\frac{D\theta}{r_m^2}$	$\frac{K}{\rho c_p}$ is thermal diffusivity, replace by mass diffusivity
m	$\frac{K}{h_T r_m}$	$\frac{cD_{AB}}{k_x r_m}$	Ratios are Nusselt numbers for heat and mass
n	$\frac{r}{r_m}$	$\frac{r}{r_m}$	Dimensional ratios unchanged

where:

c	peripheral gas concentration	P'	peripheral constant pressure
c_p	isobaric heat capacity	P_b	initial pressure within body
D	mass diffusivity	r	radius to any given point
D_{AB}	diffusivity for "gas A" through "gas B"	r_m	specimen radius
h_T	surface (peripheral) heat transfer coefficient	t	instantaneous point temperature
		t'	peripheral constant temperature
K	thermal conductivity	t_b	initial temperature of body
k_x	surface mass transfer conductance	θ	time
P	instantaneous point pressure	ρ	material density

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July 23, 1964 APPROVAL NASA TMX-53094

INTERCELLULAR MOBILITY OF FLUIDS WITHIN HONEYCOMB-REINFORCED COMMON BULKHEADS

(BULKHEAD PURGING)

By

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